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PATENT- OG VAREMÆRKESTYRELSEN

METHOD AND APPARATUS FOR MEASURING DEFORMATIONS AND FORCE OF A SYSTEM

FIELD OF THE INVENTION

The invention relates to a method for measuring deformations and force of a system. The system may be a mechanical system, a physical system or a biological system such as e.g. a bodily hollow system. The invention also relates to an apparatus for utilising the method. Finally, the invention relates to uses of the apparatus according to the invention.

BACKGROUND OF THE INVENTION

The function of visceral organs like the gastrointestinal tract, the urinary tract and the blood vessels is to a large degree mechanical. The following introduction refers mainly to the gastrointestinal tract but the invention relates to similar applications in other hollow organs and even to measurement of deformation and forces inside tissues such as in muscle, in plants and in engineered structures.

In the gastrointestinal tract, contents received from the stomach are propelled further down the intestine and mixed with secreted fluids to digest and absorb the food constituents. The biomechanical properties of the small intestine *in vivo* are largely unknown, despite the fact that the distensibility is important for normal function, and altered mechanical properties are associated with gastrointestinal (GI) diseases. Data in the literature pertaining to the mechanical aspects of GI function are concerned with the contraction patterns, the length-tension relationship in circular and longitudinal tissue strips *in vitro*, flow patterns, the compliance and the tension-strain relationship in vivo. The methods traditionally used for clinical or basic investigations of the small intestine are endoscopy, manometry and radiographic examinations. Although these methods provide important data on the motor function, little attention has been paid to biomechanical parameters such as wall tension and strain and the relation between biomechanical properties and sensation. During the past two decades, impedance planimetry was used in gastroenterology to determine wall tension and strain in animal experiments and human studies. Impedance planimetry provides a measure of balloon cross-sectional area and is therefore a better basis than volume measurements for determination of mechanical parameters such as tension and strain in cylindrical organs. Impedance planimetry, however, only provides a measure of circumferential tension and as such no measurement of axial forces (such as traction force during swallowing or peristalsis) is provided by impedance planimetry. The same accounts for manometry that provides a measurement of pressure but no axial force. A few scientific papers have described the use of a force transducer in terms of a strain gauge mounted on a probe inserted into the lumen of the

gastrointestinal tract. The purpose was to measure the axial force during contractions (swallows in the esophagus). The strain gauge technique suffers from high expenses, signal drift and difficulties mounting the strain gauges on the probe. Furthermore, a combination with balloon distension where the axial force and deformation could be correlated to the circumferential deformation and circumferential force-tension relationship was not considered.

GI symptoms are often associated with disturbances in motility and sensory function in the GI tract. Several studies attempted to investigate these properties by means of balloon distension. Unfortunately, the primary mechanism for symptoms elicited by GI distension remains unclear. It is well known that distension of the gastrointestinal tract elicits reflex-mediated inhibition and stimulation of motility via intrinsic or extrinsic neural circuits and induces visceral perception such as pain. Previous studies demonstrated that mechanoreceptors located in the intestinal wall play an important role in the stimulus-response function. It is, however, a common mistake to believe that mechanoreceptors are sensitive to variation in pressure or volume. A large variation in the peristaltic reflex and perception have been found in various studies and species suggesting that pressure is not the direct stimulus. Instead, the receptors are stimulated by mechanical forces and deformations acting in the intestinal wall due to changes in the transmural pressure. Thus, the mechanical distension stimulus and the biomechanical tissue properties must be taken into account in studies of the sensory-motor function in the intestine. It is likely that symptoms and pain are associated with forces and deformation in axial direction in a hollow organ. This puts emphasis on developing a reliable and inexpensive method to measure such properties under a range of functional states of the organ together with other measurements. By functional states means consideration of the muscle physiological state, pharmacological relaxation and stimulation of the muscle in the organ, diagnostic procedures, intervention and disease.

There is a considerable interest in improved diagnostics of motor disease of visceral organs. In particular this relates to the esophagus and diseases affecting the esophagus such as gastroesophageal reflux disease systemic sclerosis, spasms and non-cardiac chest pain. A proper test will also be relevant for use in the distal part of the stomach and the intestines in patients with dyspepsia, gastroparesis due to diabetes mellitus and irritable bowel syndrome. The group of patients with these diseases are huge, for example 10-20 percent of the population suffer from the irritable bowel syndrome.

Mechanical properties have been studied in vitro in muscle tissue strips from various organs. The strips are mounted in a small organ bath between hooks. The strip can be elongated in a controlled way and the resultant force measured. This test is often done in

the direction of the longitudinal axis of the muscle fibers. The strips studies have rendered possible studies of isometric and isotonic muscle length-tension diagrams in vitro. Usually the tissue has been studied when influenced by drugs such as muscle relaxants and muscle stimulants, in order to study active and passive tissue properties. The passive curve is normally described as exponential whereas the active curve is bell-shaped, i.e. with a maximum force at a certain strain level. The maximum active tension is presumably reached at a level of optimum overlap between the sliding filaments in the intestinal muscle cells. In vivo no such method exists for studying the properties in the axial direction of a hollow organ like the gastrointestinal tract.

DE 42 14 697 describes an electrical sensor element intended for measuring rotation, angle, flexing and displacement through its own deformation and the associated change in electrical resistance. The sensor element consists in an elastically flexible housing filled with liquid or gaseous electrolyte. In the non-deformed state, the sensor has a definite resistance, when the housing is sealed, and electrodes being connected to an electrical circuit so that current may be passed through the electrolyte. The sensor element is intended for to being used in automation of various processes, e.g. vehicle manufacture whereas no medical uses are claimed. Furthermore, DE 42 14 697 describes only a closed housing whereas at least for many biomedical purposes and for the easy of construction a perfusion system or otherwise an open system may be advantageous.

WO 03/020124 describes a method and an apparatus for stimulating and/or measuring visceral pain in a bodily hollow system of a human being or an animal. The method and apparatus is especially well suited for multi-modal stimulation and measuring, where different stimulus modalities are integrated into one stimulus device. The stimuli may be any one or more of the stimuli: mechanical stimulus, thermal stimulus, chemical stimulus and electric stimulus. The stimuli may activate superficial and deeper layers of the hollow system. Distinct responses to the individual stimuli and robust stimulus-response relations are obtained and result in the possibility of comparative studies of different visceral sensations. WO 03/020124 does not specify a specific solution for measurement of axial forces without and with combination with the multimodal stimulations and measurements.

SUMMARY OF THE INVENTION

The object of the invention may be to record deformations and force of a system in a manner ensuring reliable measuring and an apparatus eliminating or at least to a large extend reducing the number of and/or the magnitude of the disadvantages of the prior art.

This object may be obtained by a method for measuring a deformation of a system by
- introducing into the system, alternatively assigning to the system, a probe capable of at least exhibiting an elastic deformation,
- introducing into at least part of the probe a non-metallic conductor for conducting an electrical current,
- providing into the non-metallic conductor a plurality of electrodes being electrically connected through the non-metallic conductor and being applied an electrical potential,
- measuring the electrical potential difference between at least two of the number of electrodes for determining an actual electrical impedance of the non-metallic conductor between the at least two electrodes, and
- said present electrical impedance, in correlation with an empirically determined electrical impedance of the non-metallic conductor between the at least two electrodes, being indicative of a deformation such as an extension or contraction of the system.

Alternatively, the object may be obtained by a method for measuring a deformation of a system by
- introducing into the system, alternatively assigning to the system, a probe capable of at least exhibiting an elastic deformation,
- introducing into, alternatively assigning to, at least part of the probe a metallic conductor for conducting an electrical current,
- providing at last at two points along the metallic conductor an electrical connection at aech of said at least two points and said points being applied an electrical potential,
- measuring the electrical potential difference between the at least two of a number of points for determining an actual electrical impedance of the metallic conductor between the at least two points, and
- said present electrical impedance, in correlation with an empirically determined electrical impedance of the metallic conductor between the at least two points, being indicative of a deformation such as an extension or contraction of the system.

The system may be a mechanical system, a physical system or a biological system such as e.g. a bodily hollow system or a muscle. The invention also relates to an apparatus for utilising the method. Finally, the invention relates to uses of the apparatus according to the invention.

The proposed invention is based on measurement of electrical impedance which is easy to do and inexpensive. The impedance measurement in a non-metallic or a metallic conductor will correlate to the deformation of the conductor and to the force applied to the conductor.

The method according to the invention may be employed, where the empirically determined force, alternatively the empirically determined distance, is a force or a distance between the at least two of the number of electrodes, or points, measured subsequent to introducing or assigning the probe, said empirical distance measured initially to measuring the actual distance.

The method according to the invention may, alternatively, be employed, where the empirically determined force, alternatively the empirically determined distance, is a force or a distance between the at least two of the number of electrodes, or points, measured subsequent to introducing or assigning the probe, said empirical distance measured subsequently to measuring the actual distance.

In a possible way of carrying out the method according to the invention, the method comprises introducing into at least part of the probe a fluid non-metallic conductor for conducting an electrical current, and said method comprising establishment of a flow of the non-metallic conductor through the probe in order to provide a continuous introduction and extraction of fluid non-metallic conductor to and from the probe, respectively.
By establishing a flow of the non-metallic conductor, a more simple probe may possibly be used, and also, any chemical or physical changes of the conductor, when current is applied, may be avoided or reduced, when the conductor is passed to and from the probe continuously. Also, any gasses developed in a liquid electrolyte, when current is applied, and perhaps impeding the measurement of the impedance of the non-metallic conductor, may be led out of the probe together with the flow of the conductor.

The object may be obtained by an apparatus according to the invention,
- said apparatus comprising a non-metallic conductor for conducting electric currents, and a plurality of electrodes being electrically connected through the non-metallic conductor,
- said apparatus furthermore comprising means for measuring the electrical potential difference between at least two of the number of electrodes for determining an actual electrical impedance of the non-metallic conductor between the at least two electrodes.

By using a non-metallic conductor, many of the possible disadvantages of using strain gauges, piezo-electric elements and the like for measuring a deformation of a system may be avoided. One of the major disadvantages avoided is the unreliability of the strain gauge or the piezo-electric element being not properly attached to the probe used. Such non-proper attachment can be very difficult if at all possible to detect. One of the major advantages of the present invention is the possibility of choosing a non-metallic conductor being non-harmful, when measuring deformation in human or animal bodily systems.

Preferably, the non-metallic conductor is a liquid serving as an electrolyte for conducting the electric current between the electrodes, and possibly, the liquid is chosen to be non-harmful to the system together with which the probe is to be used, such as a human or animal body. In this case, a solution of NaCl is suited as a liquid non-metallic conductor.

In a possible embodiment of an apparatus according to the invention, said apparatus being provided with at least one inflatable balloon situated between a proximal end and a distal end of the probe, and the apparatus comprising means for passing an inflating fluid, preferably a liquid, more preferred an electrolyte, from the proximal end to the balloon, and where the apparatus is provided with means for measuring at least one of the following physical properties of the balloon: the volume of the balloon, the cross-sectional area of the balloon seen in a direction parallel to the longitudinal extension of the system, when the apparatus is introduced into or assigned to the system, the diameter of the balloon in a plane perpendicular to a longitudinal extension of the system, when the apparatus is introduced into or assigned to the system, the tension of the balloon, the strain of the balloon, the pressure of a fluid inside the balloon, and the temperature of a fluid inside the balloon

It is important to notice that by the denomination "balloon" is meant only a bag capable of being inflated. The inflation need not result in a dilation of the material of the balloon. Thus, perhaps the balloon is made of a material, which subsequent to inflation is not subjected to any stretching, but merely has an increased volume due to the inflation. Accordingly, in the whole of the application, apart from in the test results in the last part of the specification, the denomination "balloon" will be used, because this is the commonly used denomination, although the balloon may be as a bag, i.e. no dilation of the bag.

BRIEF DESCRIPTION OF THE FIGURES

Fig. 1 is a schematic view of an apparatus according to the invention and comprising a probe with an electrolyte and two electrodes in a non-stretched state, and the two electrodes in a stretched state, and

Fig. 2 is a diagram showing a possible relationship between an electrical potential difference between the electrodes compared to a mass applied to the probe.

DETAILED DESCRIPTION OF THE INVENTION

Fig. 1 shows schematically an elongated probe having side walls and exhibiting a hollow inner chamber or channel. The hollow chamber is filled with a non-metallic conductor, preferably a liquid electrolyte such as water with a solution of NaCl. Other non-metallic

conductors may be used, either being a liquid, a gas or a solid. Two electrodes are provided in the probe. A distance D is established between the two electrodes. The electrodes are used for measurement of the electrical impedance in the fluid between them. When the probe is stretched in axial direction (as illustrated in the bottom figure), the electrical impedance will increase due to the longer distance between the electrodes and the smaller diameter in the fluid-filled channel.

The number of electrodes may be more than two. In fact improved impedance recordings may be obtained by a four-electrode system with two outer electrodes generating a constant alternating current between them and with two electrodes placed between the other electrodes for measurement of the impedance or voltage drop between them. The distance D is determined empirically, i.e. the distance between the electrodes is preferably determined, when the probe is subjected to no externally applied forces (see fig. 2). Electrodes may also be placed opposing each other at the same circumferential level of the chamber or even at several circumferential levels in the chamber in order to provide information about forces and deformations in other directions than in the longitudinal direction such as circumfertially or transversely to the length of the system. The dectection in multiple directions provides information about more complicated deformations of the system e.g. bending, twisting, shearing or the like. Combination with pressure measurement in the chamber may be advantageous in the determination of tissue forces and deformation in various directions and in cases where the perfusion has a function in keeping the conductor channel open in very elastic probes. The chamber may also be replaced by thin conducting wires that deforms and changes impedance when the probe is deformed.

The non-metallic conductor may, as mentioned, be a gas as an alternative to a liquid, preferably a noble gas in order for the gas not to chemically react with the material, which the side walls of the probe is made of. If the non-metallic conductor is a liquid or a gas, the conductor may either be introduced into the probe before measuring and subsequently be maintained enclosed within the probe. Alternatively, also if the non-metallic conductor is a liquid or a gas, the conductor may be introduced into the probe by a flow of the conductor, and thus the amount of conductor within the probe will be constantly renewed.

The non-metallic conductor may also be a solid of some substance capable of conducting an electrical current between the electrodes. If the non-metallic conductor is a solid, the conductor may be introduced into a chamber of the probe. Alternatively, the conductor may alternatively be introduced during manufacturing of the probe so that the conductor constitutes part of the probe itself. Either, the conductor is integrated with the material,

which the probe is made of, or the probe itself is made of a material, which at the same time constitutes the non-metallic conductor. .

In case the probe is to be introduced into or assigned to a bodily system of a human or an animal, perhaps introduced into a bodily hollow system of the person or the animal. the choice of non-metallic conductor may also be chosen as a substance or a material being non-harmful to the human or animal body. Thus, a noble gas will satisfy such criteria, and the same criteria will be fulfilled by water with a suitable solution of NaCl.

When an electrical potential is applied to the electrodes, a current will run between the electrodes through the non-metallic conductor inside the probe. The electrical impedance of the non-metallic conductor along the distance between the electrodes is dependent on the choice of non-metallic conductor, the cross-sectional area of the probe and of the empirical distance between the electrodes. Thus, by measuring the electrical impedance between the electrodes, a correlation between the impedance and the distance may be determined empirically during no stretching of the probe.

Fig. 1 (bottom) shows what happens, when an external force is applied to the probe. The probe will become stretched, and the stretching will result in an increase of the distance between the electrodes and in a decrease of the cross-sectional area of the probe. The increased distance between the electrodes and the decreased cross-sectional area of the probe both result in an increased electrical impedance of the non-metallic conductor inside the probe.

By employing empirical knowledge of the physical properties of the probe during stretching or compression of the probe, and by employing the electrical properties of the non-metallic conductor, the actual distance between the electrodes during stretching of the probe can be derived. Alternatively to, or additionally to determining the distance between the electrodes during stretching, the magnitude of the force being applied can be derived.

During stretching, the actual electrical impedance of the non-metallic conductor between the electrodes is measured, and the electrical impedance will, as mentioned, be greater than the empirically determined impedance (see fig. 1, top) if the probe is subjected to a stretching. The decrease in cross-sectional area of the probe during stretching amount to some of the increase in the electrical impedance, and the increase in distance between the electrodes amount to the rest of the increase in electrical impedance.

By applying Ohm's Law, $U = R \cdot I$, where U is the potential difference between the electrodes trough the non-metallic conductor, R is the electrical impedance of the non-

metallic conductor between the electrodes, and I is the current running between the electrodes, the change in distance between the electrodes can be derived though the change of the electrical impedance, if the potential difference U and the current I is maintained unaltered both before and during stretching of the probe.

The electrical impedance R of the non-metallic conductor is determined as $R = \rho \cdot (D/A)$, where ρ is the electrical resistivity of the non-metallic conductor, D is the distance through the non-metallic conductor between the electrodes at the time of measurement, i.e. either initially for determining the empirical distance or during stretching for determining the actual distance, and A is the cross-sectional area of the non-metallic conductor, also at the time of measurement.

By applying the physical properties of the probe even further, the change in distance between the electrodes in the non-stretched state compared to the stretched state is a direct result of the force being applied to the probe. Thus, a certain change in distance between the electrodes corresponds to a certain force being applied to the probe.

Also, if the distance between the electrodes is monitored continuously together with continuously monitoring the time during which the change of distance tales place, an acceleration of the probe between the electrodes can be determined. Also, by measuring the overall change in distance between the electrodes in comparison with the empirically determined distance, and by determining the period of time for establishing the change in distance, the velocity and the acceleration may be derived.

Depending on the choice of material, which the probe is made of, and depending on whether stretching of probe is maintained within an elastic and no plastic deformation of the probe during stretching, a linear relationship between the force being applied and the change of distance between the electrodes may be obtained. Otherwise or additionally, a calibration may be needed in order to obtain any relationship between the force being applied and the change of distance between the electrodes. However, it is not inherent that the force being applied to the probe is of interest, perhaps only the change in distance is of interest. Likely a rather undeformable material, perhaps only changing 2-5% in length during the load of force, will be best for the force measurement whereas a very elastic probe material may be more suitable for the deformation of the probe and the organ under study.

Fig. 2 is a diagram showing the relationship between a force being applied to the probe in longitudinal direction and the electrical potential between the electrodes. The force is expressed as a mass, which the probe is subjected to, said mass in the embodiment of the

test being influenced by gravity only. The force is applied to a probe made of PVC, having a diameter of 4.5 mm, being a multilumen probe, and the distance between the electrodes being 10 mm in non-stretched state. The non-metallic conductor is a 0.9% solution of NaCl in water. In this experiment it is evident that the voltage difference (spænding) is directly proportional to the impedance and to the force (kraft) imposed in longitudinal direction to the probe (in the current experiment done by hanging weights in one end of the vertical oriented probe. However, in other experiments the calibration curve may be non-linear but this can easily be accounted for.

Other materials than PVC may be chosen as the material which the probe is made of. PVC and the dimensions of the probe compared to the force being applied in the diagram shown will only result in a small elastic stretching of the probe. This may be beneficial i systems where it is important that the probe is fixed in relation to the deformations of the system. Other materials and other dimensions of the probe exhibiting more profound deformations, when a certain force is applied to the probe, may be suitable in systems, where it is important that the probe itself do not impede the deformations of the system. Depending on the mechanical properties of the probe itself, it may be necessary to correct for the material properties of the probe before a force or deformation of the bodily system can be determined with accuracy.

In the schematic embodiment shown in fig. 1, and the results in the diagram in fig. 2 is based on an elongated probe, and in a change in a longitudinal distance between the electrodes. However, alternatively hereto, the probe may have other shapes than elongated probe such as round, ellipsoidal or cubic. Alternatively to or in addition to measuring the change in longitudinal distance between the electrodes, the distance being measured may perhaps be a circumferential distance along the circumference of the probe or a transverse distance along a cross-section of the probe, and said alternative or additional distance being non-dependant on the shape of the probe. This is useful both in cases where the probe is used in hollow organs and in cases where the probe is embedded into a tissue such as a muscle or the liver, in plants or into an engineered structure.